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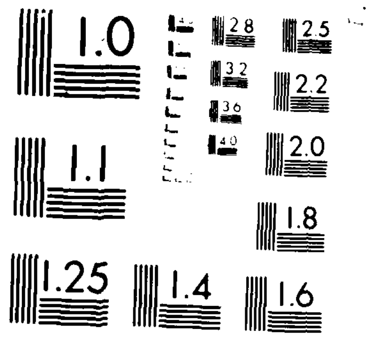

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CLASSIFICATION OF SOLAR FLARES AND RELATIONSHIP BETWEEN THE FIRST AND SECOND PHASES

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ABSTRACT

A large data base on solar flares obtained during the last solar maximum years makes it necessary to revise our views on the relationship between the impulsive phase and the second phase of flares. Contrary to the view most popular before the launch of the *Solar Maximum Mission*, we now know that relativistic electrons and γ-ray-producing protons and ions are accelerated during the impulsive phase. Because flares producing nuclear γ rays are different from ordinary flares, I conclude that additional processes take place in γ-ray-line flares. In my recent studies I have shown that flares with gradual hard X-ray time profiles not only produce nuclear γ rays during the impulsive phase but also develop full-fledged second-phase phenomena. ~~I propose that~~ filament eruption plays a key role in γ-ray-line flares. When an erupting filament interacts with an overlying flare loop, relativistic electrons and energetic protons are produced during the impulsive phase. When the erupting filament fully distends the overlying flare loop, full-fledged second-phase phenomena, such as shocks, interplanetary energetic particles, mass ejections and etc. are observed. When the overlying flare loop is compact and strong enough to supress the activated filament, γ-rays are emitted during the first phase but no second-phase phenomena occur.

INTRODUCTION

During some flares, several minutes after the initial impulsive energy release, additional energy release is obse ... The additional energy release is evidenced by type II and type IV radio bursts. Type II emission has been interpreted as being due to relativistic electrons accelerated by shock waves propagating in the corona. Several hours after flares producing metric type II bursts, polar cap absorptions (PCAs), which are due to energetic protons, are often observed. Because of high correlations of PCAs or ground-level events (GLE) with type II and type IV radio bursts, it was proposed that energetic protons as well as relativistic electrons are accelerated during the second phase of flares /1,2/. As opposed to the second phase, we may call the period of impulsive energy release first phase. Therefore, the terms impulsive phase and first phase can be used interchangeably. However, the terms gradual phase and second phase should not be used interchangeably. Virtually all flares have a gradual phase, but only a small fraction of flares exhibit a second phase.

After above-mentioned papers, more works showing good association between type II or type IV radio bursts with interplanetary solar energetic particles have been performed /3,4/, and references therein/, and attempts have been made to interpret hard X-ray and γ-ray observations of various flares in terms of two phases of acceleration by many researchers /5,6,7,8/. The concept of two acceleration phases was fully accepted in a textbook on solar flares /4/, and it has become a canonical view in a Skylab Workshop monograph on solar flares /9,10/.

The concept of two phases of acceleration has been widely accepted to a degree that it can be called a paradigm. Before discussing new observations in conflict with the old paradigm, let us summarize the canonical view of the old paradigm of two phases of acceleration.

(1) There exists two phases of acceleration in some flares: first and second phases.

(2) During the first phase, electrons are rapidly accelerated up to about 200 keV. But during this phase electrons are not accelerated to relativistic energies, nor are protons accelerated to energies above MeV.

(3) In some flares, a second phase of acceleration takes place. During the second phase, relativistic electrons and protons with energies above MeV are accelerated in the corona by shocks. These electrons produce type II and type IV radio bursts, and these protons propagates into interplanetary space and arrive at the Earth to cause PCAs and GLEs.

(4) Energy released in the first phase causes the second phase. Wild, Smerd, and Weiss /1/ proposed that an unspecified explosion occurring in the lower solar atmosphere during the first phase propagate outward to produce shocks in the corona. Lin and Hudson /11/ proposed that a thermal explosion due to rapid energy deposit in the chromosphere by electrons accelerated during the first phase produces shock waves.

CHALLENGE TO THE OLD PARADIGM

Now let us discuss recent observations which cannot be readily explained with the old paradigm summarized above. First, observations made with *HEAO 1*, *HEAO 3*, and *SMM* made it clear that protons and ions as well as electrons are rapidly accelerated to energies above MeV/nucleon during the impulsive (first) phase /12,13,14,15,16/. Although, this was first noticed from observations of *HEAO 1* and *HEAO 3*, *SMM* GRS observations of many γ-ray-line flares brought this point to us with a full impact. These observations are in contradiction with the old view that relativistic electrons and protons above MeV are only accelerated during the second phase. Because of these observations, some researchers even expressed doubts on the reality (or necessity) of the second-phase acceleration /8,14,16/. Even if we do not deny the reality of the second-phase acceleration, we do not know how to put the first-phase acceleration of relativistic electrons and protons above MeV within the old paradigm. One view is that all flares accelerate relativistic electrons and protons above MeV during the impulsive phase /15,16/. An alternative view is that during only a small fraction of flares relativistic electrons and protons above MeV are accelerated during the first phase /17,18,19,20,21,22/.

Second, another challenge to the old paradigm is that the first phase is not likely to be the cause of the second phase. This point was first raised by careful studies of energetics of a well-observed two-ribbon flare of 1973 September 5 (Apendix A, B of /10/). It was shown that energies involved with mass motions (second-phase phenomena) far exceed the total radiative energy observed during the first phase. It was also shown /23/ that some flares producing large fluxes of interplanetary energetic protons (second-phase acceleration) exhibit very weak impulsive-phase radiations (microwaves and hard X-rays). Furthermore, according to the thermal explosion model of Lin and Hudson /11/, flares with a rapid energy deposit by energetic electrons in small chromospheric areas are likely to develop second-phase phenomena. However, flares with full-fledged second-phase phenomena show opposite characteristics: such flares show gradual hard X-ray time profiles, large Hα areas, and hard X-ray emission in the corona (cf. /21/).

A NEW PARADIGM:
DIFFERENT CLASSES OF FLARE AND ASSOCIATED PHENOMENA

It has been controversial since the early days of *SMM* /15,18/ whether only certain flares accelerate γ-ray-producing protons during the first phase or whether all flares do so and only the threshold of the γ-ray detector distinguishes γ-ray-line (GRL) flares from the rest. In order to convincingly show that one group of flares are different from others and belong to a separate class, one has to study systematically many aspects of large numbers of flares. That is precisely what one of my colleagues and I have done in our recent studies /20,21/. I have systematically studied various properties of all the 17 GRL flares observed in the 1980–1981 period, 23 gradual γ-ray/proton (GR/P) flares observed during 1980–1982, and, as a comparison group, 29 intense hard X-ray flares (peak HXRBS rates greater than 10000 counts s^{-1}) but without detectable nuclear γ-rays (cf. Tables 1–3 of /21/). Additionally, hard X-ray spectral indices of all the 1980–1981 flares with peak HXRBS rates above 1000 counts s^{-1} were included in the study. Based on such studies, I have concluded that GR/P flares share common characteristics which distinguish them from other flares.

Characteristics of GR/P flares are summarized in Table 1. The first four characteristics are common to both impulsive and gradual GR/P flares. Gradual GR/P flares exhibit additional characteristics not shared by impulsive GR/P flares (No. 5–17 of Table 1). Among the differences between impulsive and gradual GR/P flares, fundamental differences are in that gradual GR/P flares exhibit full-fledged second-phase phenomena while impulsive GR/P flares no second-phase phenomena other than coronal type II and type IV radio bursts. Impulsive GR/P flares often produce type II and type IV radio bursts, which indicate production of coronal shocks, but the coronal shocks produced by impulsive GR/P flares do not develop into interplanetary shocks. (Note that Maxwell and Dryer /24/ proposed that there may be two types of coronal shocks: blast wave shocks and piston-driven bow shocks.) The differences between impulsive and gradual GR/P flares regarding first-phase phenomena are not of fundamental nature but stem from larger spatial and temporal scales of gradual GR/P flares.

What I call gradual GR/P flares here have been recognized as constituting a separate class from various observational aspects. From Hα properties they are called two-ribbon flares; from soft X-ray time profiles, long-decay events (LDE); from Skylab soft X-ray imaging observations, diffuse X-ray flares; from acceleration of energetic protons detected in interplanetary space, proton flares; and from coronal emission of hard X-rays, coronal hard X-ray flares /4,21,25, and references therein/. And correlations between various aspects of these flares have been studied by many researchers /4,21,25/. My unique contirbutions from analyses of *SMM* observations to the understanding of gradual GR/P flares are (1) their production of nuclear γ rays during the first phase, (2) their unique characteristics appearing in hard X-ray emission (first phase phenomenon), and (3) relationship between proton acceleration during the first phase and second-phase acceleration (which will be discussed below). Following Tanaka /26/, I divide non-GR/P flares into thermal and nonthermal hard X-ray flares. I have found that none of the *SMM* flares observed in 1980 with hard X-ray spectral indices greater than 6.5 (most likely thermal hard X-ray flares) produced type II or type IV bursts. Mainly based on *Hinotori* hard X-ray imaging and spectral data, Tanaka /26/ classified flares into type A (thermal hard X-ray) flares, type B (nonthermal hard X-ray flares), and type C (coronal hard X-ray) flares. Type C flares correspond to gradual GR/P flares of my classification, and type A flares are obviously thermal hard X-ray flares. Type B flares correspond to impulsive GR/P flares and nonthermal hard X-ray flares. Tanaka /26/ did not perform a systematic study of various properties of a large number of flares to be able to resolve differences between impulsive GR/P flares and non-GR/P flares. However, his study added new information that gradual GR/P flares emit hard X-rays from high in the corona ($\geq 10^9 cm$).

In Table 2, flare classes and their characteristics are listed according to the first and second phase phenomena. We can see that only gradual GR/P flares develop full-fledged second-phase phenomena.

Now that we have classified flares and attendant properties, let us discuss what processes make GR/P flares different from others. Many researchers have recognized the importance of filament eruption in gradual GR/P flares (i.e., two-ribbon flares, proton flares, LDE flares) (e.g., /4,27,28/). Full eruption of filaments causes shocks (which in turn accelerate second-phase particles), mass ejections, and long-decay soft X-ray events by slow reconnection of magnetic fields distended by an erupting filament, and spreading two-ribbon flares /28,29/. But the first three characteristics of graudual GR/P flares in Table 1 (which are in common with impulsive GR/P flares) have not been explained so far with an erupting-filament model. (They have been found only after the launch of *SMM*.) I propose the following. When an erupting filament pushes an overlying flare loop violently, shock waves and tublulence develop within the flare loop, and they in turn accelerate electrons and protons further (this process has been called "second-step acceleration" /17,18,21/). During impulsive GR/P flares an activated filament interacts with the overlying flare loop and the second-step acceleration takes place, resulting in γ-rays, flat hard X-ray spectra, and soft-hard-harder behavior of hard X-ray spectra. While in gradual GR/P flares the erupting filament distends fully overlying flare loops to cause reconnection at the neutral sheet and full-fledged second-phase phenomena /28/, in impulsive GR/P flares the overlying flare loop is rather low and its magnetic field is strong enough to prevent the erupting filament from distending the overlying field. Therefore, in impulsive GR/P flares which are known to be compact in spatial scales, full-fledged second-phase phenomena do not develop. Following this scenario, then in non-GR/P flares filaments are not activated or even if they are, they do not play an important role.

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TABLE 1 Impulsive and Gradual Gamma-Ray/Proton Flares

No.	Categories	Impulsive Flares	Gradual Flares	Comments
1	Nuclear γ rays	Yes	Yes	a
2	H.X.R. spectrum	Hard ($\langle\delta\rangle \sim 3.3$)	Hard ($\langle\delta\rangle \sim 3.5$)	a
3	H.X.R. spectral hardening	Some (6 of 13)	Yes (22 of 23)	a
4	Association with type II or IV	Good (9 of 13)	Good (20 of 23)	a
5	High-energy delay	Short (<4 s)	Long (> 8 s)	b
6	H.X.R. spike duration	< 90 s [c]	> 90 s	b
7	H.X.R. total duration	< 10 min	> 10 min	b
8	Soft X-ray duration	< 1 hour	> 1 hour	b
9	Hα a. ea	Small	Large	b
10	Loop height	Low (< 10^9 cm)	High (> 10^9 cm)	b
11	Microwave richness index[d]	< 1.0	> 1.0	b
12	Average type II duration	14 min	25 min	b
13	Proton ratio (I.P./γ ray)	Small ($\ll 1$)	Large ($\gg 1$)	b
14	Interplanetary shock	No	Yes	b
15	Coronal mass ejection	Some	Yes	b
16	$[e/p]$ ratio	Large	Normal	b
17	I.P. proton flux decay	Rapid (hours)[e]	Slow (days)	b

[a] Common to both impulsive and gradual GR/P flares.

[b] Impulsive and gradual GR/P flares are different in these properties.

[c] Mostly < 30 s.

[d] Microwave to hard X-ray peak flux ratio. For definition, see reference /21/.

[e] Only a small fraction of impulsive GR/P flares produce detectable I.P. energetic particles.

TABLE 2 First and Second Phase Phenomena in Different Classes of Flare

First Phase	Second Phase
1. Gradual GR/P Flares	
Nonrelativistic electrons	Type II radio bursts
Relativistic electrons	Type IV radio bursts
Energetic protons and ions	Coronal shocks, I.P. shocks
Nuclear γ rays	I.P. energetic particles
Soft-hard-harder behavior of H.X.R. spectra	Coronal mass ejections
Flat hard X ray spectra	Long-decay soft X-ray emission
2. Impulsive GR/P Flares	
Nonrelativistic electrons	Type II radio bursts
Relativstic electrons (I.P. electrons)	Type IV radio bursts
Energetic protons and ions (Low flux I.P. protons)	
Nuclear γ rays	
Soft-hard-harder behavior of H.X.R. spectra	
Flat hard X-ray spectra	
3. Nonthermal Hard X-ray Flares	
Nonrelativistic electrons	Type II radio bursts (rare)
No γ rays	Type IV radio bursts (rare)
Soft-hard-soft behavior of H.X.R. spectra	
Steep hard X-ray spectra	
4. Thermal Hard X-ray Flares	
Thermal electrons	No type II, no type IV

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